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ELECTROMETRIC TUBES

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[Figures referred to herein are appended.]

Introduction

The insignificant amount of energy expended in electronic tubes, in controlling the electronic current from the cathode to the plate with the aid of a control grid, has made it expedient to use electronic tubes for measurement purposes, particularly for measuring extremely weak currents. Not only special types of electrometric tubes, but also certain ordinary electronic tubes in mass production, are used in radio engineering. They are successfully competing with the most sensitive galvanometers and with various types of electrometers, and are simplifying the techniques of making measurements and handling the corresponding electrometric apparatus.

Following initial attempts to construct sensitive electrometric circuits from ordinary triodes and the most complex multigrid tubes, special electrometric tubes were developed. Further developments of vacuum tube electrometers is taking place along two lines. Side by side with the design of increasingly perfected electrometric tubes, we see numerous examples of the application of ordinary electronic tubes in special electrometric circuits and corresponding systems. Therefore, in the present survey we shall examine the construction and parameters of special type electrometric tubes which have appeared in the last 10 to 15 years. We shall also scan briefly the application, for electrometric purposes, of various types of electronic tubes in mass production.

The basic requirements for electronic tubes to be used in electrometric circuits are: minimum value of grid current detecting the smallest quantities of current practicable for measuring with the aid of such tubes, and stability

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of tube operation. The first requirement determines the selection of the construction and operating conditions of the tube. The fulfillment of the second requirement is also dependent upon the tube circuit. Therefore, before discussing the characteristics of existing types of electrometric tubes, it is advisable to examine in detail the possibility of reducing grid current as much as possible in present-day electronic tubes, and to examine the question of the operating stability of the tubes in the circuit.

A. Grid Currents -- Classifications, Causes, and Methods for Lowering

Hereafter, in referring to the control grid and grid currents, we shall have in mind the controlling electrode in the very general case and currents in its circuit with negative potential on the electrode. For example, triodes are used very frequently in electrometric circuits included in so-called inverted triode systems, where the grid, which is located closer to the cathode, plays the role of a plate or collector of electrons and the plate of the tube is the controlling electrode. Since, for positive or small negative (up to -1.5 v) voltages on the controlling electrode, an appreciable part of the electron current emitted by the cathode falls into it, this tube operating condition is not of interest from the viewpoint of applicability to electrometry. We shall limit ourselves to an examination of cases with sufficiently large negative bias on the control electrode.

Among the electrons emitted by the cathode, there will always be found some which possess sufficient emission velocity to overcome the effective negative potential of the control grid. Their number decreases as the negative potential on the grid increases, and at the same time the grid current falls exponentially.

In practice, however, this electron component of the grid current is partially compensated for by its other components which are usually present. With a certain bias on the control grid, called "the free-grid potential," the grid current curve ($I_{g\Sigma}$, Figure 1) passes through the zero value, and with sufficiently large negative bias a grid current in the reverse direction is observed. The nature of this grid current proves to be much more complicated than seems apparent at first glance.

In any electronic tube the grid current is made up of the following components:

1. Grid electron current created as a result of the initial emission velocity of the electrons from the cathode surface.

2. Grid ionization current, i.e., a current of positive ions formed when the electrons collide with the atoms and molecules of the residual gas in the tube.

3. The current leading along the insulation between the control grid and remaining electrodes in the tube.

4. Electron emission current from the grid which results when the grid heats to a temperature at which this current becomes noticeable. As a rule, this current is observed only in tubes with heater-type oxide cathodes in which the grid, after being heated up considerably, is found to be activated due to the accumulation on it of a large amount of active material from the cathode.

Beside this, in special tubes with small grid currents, it is possible to observe other causes of grid current formation:

1. Photoelectric emission current from the grid produced by (a) light emanation from the cathode, (b) illumination of the tube electrodes from without, (c) soft X-ray radiation emerging from within the tube.

2. Ionization emission current from the cathode.

We shall examine separately the enumerated components of grid current and the possibility of decreasing them.

The grid electron current (Ige) in the case of triodes, as is known, is expressed by the equation:

$$I_{ge} = m \cdot I_e \exp\left(\frac{eU_g^*}{kT_k}\right) \quad \text{for } U_g^* \leqslant 0, \tag{1}$$

where I_e is the cathode emission, m is a dimensionless multiplier dependent on the geometric dimensions of the electrodes, and, above all, on the amount the grid is filled up with its turns, i.e., on the relationship between the diameter of the wire forming the grid and the pitch of its winding. Beside this, the quantity m depends, as experiment shows, on the plate voltage; namely, it drops with an increase in plate voltage and is completely independent of grid potential. T_k denotes the cathode temperature, e is the electron charge, k -- Boltzmann's constant, and U_g^* -- the potential of the control grid.

This equation holds true, of course, only with negative values for U_g^* representing the negative bias U_g applied to the grid, with a corresponding correction for the contact difference of potential U_k between the cathode and the control grid, and for the value of the minimum potential U_m formed by the electron space charge between the cathode and the grid. Consequently, the following relationship must take place:

$$U_g^* = U_g + U_k + U_m \leqslant 0, \tag{2}$$

where U_k represents the difference in the emission work of the surfaces of the cathode and grid.

As can be seen from (1), the lower the cathode temperature, the higher is the rate of decrease of the current with an increase of the negative bias on the grid. From this viewpoint it is efficacious to use cathodes which operate at lower temperatures, to decrease the grid electron current. Therefore, in the first types of electrometric tubes we find cathodes of thoriated tungsten, used at the present time in most types of these tubes. But oxide cathodes have an operating temperature only half as large (800 - 900° K in place of 1700 - 1850° K for thoriated cathodes) and have been utilized recently in a series of special electrometric tubes, despite the danger of photoelectric effect caused by an accumulation of active material on the grid from the cathode.

The ionization currents (I_{gi}) arising, due to the ionization of the residual gases, can be considerably reduced by using sufficient active absorbents in the tubes - getters such as magnesium and barium. In most cases only magnesium is used in the special electrometric tubes, since barium can easily cause photoelectric effect in the control grid, or leakage along the insulation of the latter due to its accumulation on the insulators.

Nevertheless, the basic method, not only for lowering but also for practically complete elimination of ionic current, is to operate the tubes with voltages on all electrodes not exceeding the ionization potentials of the majority of the residual gases in the tubes; i.e., first and foremost, the component parts of the atmosphere (O_2, N_2, and Ar) and after this, gases given off by the tube parts (CO, CO_2, H_2O, H_2 and sometimes certain hydrocarbons). Therefore, in the majority of the cases the plate voltage in electrometric tubes does not exceed 8 - 1[illegible]. The guarantee of sufficiently good parameters is attained by the general usage of "double grid" tubes as electrometric tubes, i.e., tubes with a first antispace-charge or cathode grid which is under a small positive potential (4 - 6 v), and with a second control grid. In the case of triode applications, they are more frequently used as inverted triodes, i.e., a positive voltage is applied to the grid and the plate serves as the control electrode. As examples of double-grid and inverted triodes we may take, respectively, one of the first electrometric tubes of Hausser [1] and Type A 154 RCA tube. Sometimes, as can be seen from the Philips Type 4060 tube, the plate and control electrode are arranged in the form of two sheets on either side of the cathode, the so-called "plation," [2], at different distances (control electrode closer to the cathode than the plate). In all of the enumerated designs it is possible to obtain the necessary parameters with plate voltages of the order of 4 - 6 v, and in any case not higher than 8 - 10 v.

As numerous experiments show, ionic grid currents are proportional to the value of plate current and pressure of the residual gases in the tube [3]. Nevertheless, in most cases in which tubes are utilized in electrometric circuits, the currents produced by the ionization of the gas are practically absent, and the insignificant ionic current produced in certain cases owes its origin, as we shall see below, to emission of positive ions by the cathode.

The grid leakage currents ($I_{g\sigma}$), i.e., the quality of its insulation with respect to the other electrodes, can be brought to practically any desired value by various means. In essence, minimum values are determined by the tube dimensions and the voltages applied.

In special electrometric tubes, as a rule, the control grid is braced inside the tube on special insulators, glass or quartz, and the control grid lead is usually through a dome on the glass envelope. Apart from the leakage currents along the internal tube leads, leakage also takes place along the glass envelope and along its outside surface. In order to decrease the leakage along the glass envelope in certain tubes, as for example in tubes Type D96475 (Western Electric) [4], a long glass tube of small diameter is welded on the envelope dome through which passes the control grid lead. To avoid the accumulation of metallic conducting deposit on the inside wall of the tube, its lower opening is covered by a small metallic disk. The insulators on which the control grid is supported can be either in the form of straight rods, or bent for the purpose of lengthening the leakage path.

For protecting the insulators from an accumulation of metallic deposit, glass hoods will serve, or else special petticoat insulators are used. Sometimes the metallic holders which support the insulators are provided with separate leads on which potentials are applied, when the tube is placed in a circuit, equal to the average operating potential of the control grid, which makes it possible to reduce considerably the leakage along the insulator inasmuch as both of its ends are found practically under the same potential.

Due to the above measures, the only basic leakage which remains is that along the outer surface of the envelope. To reduce this leakage it is recommended that the tube bulb be carefully washed with clean alcohol and then dried by heating in a desiccator. Besides this, the insulation properties of the envelope surface can be significantly improved by covering it with a thin layer of paraffin. Recently, various organic silicate compounds, applied in thin layers to the envelope, have been used for the same purpose [5, 9]. These protective coatings, preventing the glass surface from absorbing moisture which would greatly lower its insulation strength, are particularly necessary in cases where ordinary electronic tube types are used as electrometric tubes.

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Beside this, to decrease the leakage along the envelope it is advisable to put on it a protective metallic ring in the form, for example, of a glued band of tin-foil or a layer of aquadag (graphite). A metallic glass base which is used on some tubes can also serve the purpose. The protective rings, or glass bases, are either grounded or else a potential is applied to them which is equal to the average operating potential of the control grid (Figure 2).

Thermionic emission of the grid (I_{gr}) in special types of electrometric tubes is practically always absent for two basic reasons: first, economic, direct-heated cathodes are used for the most part, i.e., thoriated tungsten or oxides; and second, the operating temperature of the cathode is always selected as low as possible, i.e., of the order $650 - 700^{\circ}K$ for oxide cathodes and $1,650 - 1,750^{\circ}K$ for thoriated tungsten. Beside this, the grid which is located nearest to the cathode usually plays the role of the anti-space-charge grid or, in the case of the inverted triode, the role of an anode while the second grid or the plate is the control electrode. This results in its temperature always being sufficiently low and, even in the case of tubes with heater-type oxide cathodes, thermionic emission from the control grid is practically nonexistent.

The four basic components examined by us give the usual picture of grid currents as shown in Figure 1. In the case of special electrometric tubes, or in using ordinary tubes in electrometric systems, ionic current and thermionic emission of the grid, as was shown above, are absent and the grid currents usually are composed only of electron current and leakage current (Figure 3). With these conditions, other weaker components indicated above began to play a significant role.

Photoelectronic emission from the grid under the influence of cathode radiation is almost completely excluded, since in the case of the oxide cathode, where the activity of the grid surface can be sufficiently high, the wave length of the cathode radiation lies beyond the limits of the red boundary of photoelectric effect. In the case of thoriated tungsten, the activity of the grid is always sufficiently low.

In order to eliminate photoelectric effect from grids under the influence of external light, it is advisable to insert the electrometric tubes in light-tight covers. In the case of tubes with oxide cathodes, the photoelectric effect of the grid, as well as its thermionic emission, is considerably weakened by covering the grids with a layer of carbon (carbon black or graphite).

Finally, photoelectronic emission from the grid can also be produced by soft X-ray radiation originating in the tube itself. It may be substantial not only at plate voltages of the order of 30 - 80 volts but also voltages of the order of only 10 - 12 - 15 volts, in which case ultra-soft X-ray radiation is completely adequate to create photocurrents comparable with other components of grid current. This explains the sharp rise of grid current with plate voltages in excess of 8 v (Figure 4) prior to ionization of the residual gases. Apart from other reasons, this circumstance also compels us to limit plate voltages in electrometric circuits to values of the order of 6 - 8 v.

Ionic emission from the cathode is possible for cathodes of various types. Since, in the case of pure or thoriated tungsten, it is produced for the most part by volatile impurities in the metal, it therefore decreases sharply with time. With a satisfactory processing of the cathode it is entirely absent. In the case of oxide cathodes it takes place continuously due to the uninterrupted electrolysis of the oxide layer occurring under the influence of the emission current with a separation of oxygen ions. This effect is also caused by vaporization from the cathode surface of both metallic barium and its oxides, accompanied by partial ionization.

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The ionic emission currents from the cathode may be insignificant due to the selection of a cathode with a low current estimated at a few tens of microamperes and use of low plate voltages which produce a gradient on the oxide layer portion of the filament insufficient for electrolytic dissociation of the barium oxide. Another factor is the low cathode temperature which limits the process of vaporization of its oxide layer. Beside this, because of the application of a positive potential on the grid closest to the cathode, the positive ions flying out of the cathode for the most part return to the cathode, which prevents them from falling on the control electrode.

Finally, in the case where electrometric tubes are used as the first amplification stage for Geiger-Mueller counters, the possibility should be pointed out of the counter's operation being affected by the influence of radio-active radiation of the thorium present in the tube in the case of a thoriated tungsten cathode. In this respect, the oxide cathode has an advantage over the thoriated cathode. The absence of direct indications, in publications, of a similar effect is explained apparently by the remarkably small intensity of this radiation and practical impossibility of discerning its influence on the operation of the counter from the influence of numerous other factors caused by the so-called background of the counter.

B. Basic Types of Electrometric Tubes

In connection with the wide application of tube-type electrometric circuits which permitted the measurement of remarkably small currents down to values of 10^{-15} to 10^{-17} amps, and to detect even weaker currents, a significant number of special electrometric tubes were developed in recent years which satisfied the very diverse conditions for their application.

With respect to their construction, all these tubes can be divided into three groups: tetrodes of the double-grid type, i.e., with a positive cathode grid; triodes operating on the inverted triode scheme, i.e., with a well-insulated plate; and triodes of the "plation" type, i.e., with two plates located on either side of the cathode. The first group of tubes were most widely utilized, and apart from ordinary tetrodes there began recently the application of specially developed twin tetrodes [6, 7, 8] used in a balanced circuit and permitting the attainment, as we shall see in section C, of extremely high stability of operation of the electrometric circuits with great sensitivity.

The basic construction data of the main types of electrometric tubes are listed in Table 1. The parameters for tetrodes and triodes are given in Tables 2 and 3. Apart from the normal conditions recommended for the separate tube types, Table 4 shows examples of special conditions with greatly lowered operating voltages and cathode temperatures, permitting a considerable decrease of the limiting values of currents accessible for measurement.

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Table 1. Basic Construction for Electrometric Tubes

Tube Type	Name	Cathode	Insulator Material, Design	Basic Use	Grid Current (Amps)	Firm or Country	Notes
(Without type No)	Dual grid	Tungsten pure	Glass bent	Proportional counter electrometry	10^{-12}	Hausser	[1, 14]
T 113	"	Thoriated tungsten	Glass straight	Electrometry	10^{-13}	AEG Osram	[10, 14]
T 114	"	"	Glass petticoat	"	10^{-14}	"	[10, 14]
T 115a	"	Tungsten pure	Glass bent	Proportional counter	10^{-11}	"	similar to Hausser tube [10, 14]
4060	Triode "Plation"	Oxide direct heated	"	Electrometry	10^{-14}	Philips, Mallard	[14]
D96475	Dual grid	Oxide heater	Glass petticoat	"	10^{-15}	Western Electric	[4]
FP54 UX54	"	Tungsten thoriated	Quartz straight with protective tube	"	10^{-15}	GE Mazda	[11]
RH505	Triode	"	Glass intricate	Electrometry, proportional counter	10^{-15}	Westing-house	
RH506	"	"	"	"	10^{-12}	"	
RH507	"	"	"	"	10^{-12}	"	[13]
A'54A	"	Oxide direct heated	Glass and quartz beads	Proportional counter	10^{-13}	RCA	[12]
VX41	Dual grid sub-miniature	"	Glass	Portable proportional counter, electrometry	10^{-14}	Victorin	[9]
CK570AX	Triode sub minature	"	"	"	5.10^{-13}	Raytheon	
CM2	Dual grid	Tungsten thoriated	Glass bent	Electrometry	10^{-13}	USSR	[10]
ЭМ1	"	"	Quartz petticoat	"	10^{-14}	"	
ЭМ2	Dual grid small size	"	Quartz straight	Portable electrometry	10^{-13}	"	

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Table 2. Basic Parameters of Electrometric Tubes (Tetrodes)

Type	U_f (v)	I_f (ma)	U_a (v)	U_{g1} (v)	U_{g2} (v)	I_a (mu a)	S (mu a/v)	I_{g2} (a)	μ	C_{g2} (mmfd)	R_i (ohms)	Height (mm)	Diameter (mm)
Hausser tube	3	--	8	8	-4	300	300	10^{-12}	--	--	--	~170	~50
T 113	3	100	10	10	-3	--	180	10^{-13}	2.5	--	13,800	--	--
T 114	2	90	6	4	-4	--	55	10^{-14}	1.0	--	18,000	--	--
T 115	2.8	500	12	12	-3	--	200	10^{-11}	2.5	--	12,500	--	--
D96475	1.0	270	4	4	-3	--	40	10^{-15}	--	--	--	155	50
FP54) UX54)	2.5	90	6	4	-4	40	25	5.10^{-15}	1	~6	40,000	160	40
VX41	1.25	10	4.5	4.5	-3	<250	20	5.10^{-15}	1	--	50,000	~40	~10
СИ 2	3	110	10	6	-4	500	300	10^{-15}	4.5	~3	15,000	150	50
Э M1	3	110	10	6	-4	300	55	$<10^{-14}$	1.65	~3	30,000	160	52
ЭM2	2	80	10	6	-4	300	55	10^{-13}	1.65	~2.5	30,000	80	30

Table 3. Basic Parameters of Electrometric Triodes

Type	U_f (v)	I_f (ma)	U_a (v)	U_g (v)	I_a (mu a)	S (mu a/v)	I_g (amps)	μ	C_g (mmfd)	R_i (ohms)	Height (mm)	Diameter (mm)
A154A	1 - 1.25	170 - 195	4.75	-6	350	50 - 60	2.10^{-14}	--	--	--	120	~ [illegible]
4060	0.56	1,100	4	-4.5	50	30	2.10^{-15}	0.5 - 1.0	--	~30,000	142	58
PH505	2.0	250	6	-3	300	75	10^{-15}	1.0	3	7,500	160	52
RH506	2.5	250-	6	-3	400	90	10^{-12}	0.8	4	8,900	127	40
PH507	2.0	60-	6	-3	200	60	2.10^{-12}	0.8	4	13,000	127	40
CK570 AX	0.625	20-	12	-3	220	125	$<5.10^{-13}$	1.5	--	6,000	~ 40	~ [illegible]

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Table 4. Examples of Operating Conditions of Electrometric Tubes Permitting a Lowering of Threshold Currents Accessible for Measurement.

	FP 54		A154A	
U_f (v)	2.5	1.2	1.25	1.0
U_a (v)	8	6	4.75	3.2
U_g cathode grid (v)	6	3	--	--
I_g control (amps)	$< 5 \cdot 10^{-15}$	$2 \cdot 10^{-17}$	--	--
U_g control (v)	-4	-6	-6	-5
R_{g1} working (ohms)	10^{14}	10^{18}	10^{14}	$5 \cdot 10^{14}$
S (mu a/v)	70	0.05	50 - 60	45
Sensitivity of apparatus in the plate circuit in amps/mm	10^{-10}	10^{-10}	microammeter scale	
I_a (mu a)	--	--	350	100

As can easily be seen from the tables, the tetrodes make it possible to attain the highest sensitivity in electrical circuits. Nevertheless, less sensitive circuits are needed very frequently in the current range from 10^{-9} to 10^{-12}--10^{-13} amps. They are cheaper, simpler in operation, and more stable mechanically while operating in portable systems. For this purpose, it is possible to utilize successfully not only special triodes, but certain types of ordinary tubes in individual cases. In the latter case, it is frequently necessary to select tubes with the smallest possible leakage between electrodes.

In connection with the wide usage of light portable electrometric layouts and of portable proportional meters for various radiation, special type small-sized and even subminiature electrometric tubes were developed. Apart from small-dimension measurements they possess extremely small current requirements for cathode heating, which allows the use of miniature batteries for this purpose. Thus, for example, the subminiature tube Type VX 41 /9/ requires in all only 13 milliwatts of power for cathode heating. The cathode of this tube -- oxide with a core of nichrome wire of 10 micron diameter -- has a total filament current of only 10 ma. Despite small dimensions and control grid lead at the same end of the envelope as the other electrodes, this tube has a grid current of not more than 10^{-14} amps which is accomplished by covering the tube envelope near the lead outlets with a thin coating of organic silicate compound. In case the surface of an envelope of this type becomes soiled, it is sufficient to wash it with pure alcohol to remove the impurities without dissolving the organic silicate coating. After washing the tube with distilled water, it is necessary to heat it in a desiccator at a temperature of around 100°C.

Finally, it should be noted that, due to the same insulating conditions for the lead of all electrodes (or, what is sufficient, of both grids), tube VX 41 can be used in various hook-ups, as an electrometric tetrode, inverted triode, and a triode with large and small amplification coefficient. The selection of one or the other of these schemes depends on its use and the desired range of current measurement.

C. <u>Operating Stability of Electrometric Tubes and Means for Increasing It</u>

The basic causes of poor operating stability of electrometric tube circuits are:

1. Instability of the circuit elements, chiefly the resistors (in particular high-ohmic) and various types of contacts and compounds.

2. Instability of the insulation of separate circuit elements, in particular the tubes.

3. The presence of external influences of electric and magnetic fields.

4. Instability of the supply source.

5. Emission instability of the cathodes of the electrometric tubes.

6. Inadequate mechanical sturdiness and rigidity of construction of different type tubes.

An examination of the first four reasons does not enter into the problem of the present survey and we shall limit ourselves here to brief comments only. To secure stability for various types of contacts and compounds in electrometric circuits, it is necessary to solder carefully, avoiding both sliding contacts and adjustable conductors under clamps.

The second and third causes of poor operating stability include lack of care in shielding the electrometric tubes themselves, or the circuit elements from each other, the cleanness of the insulating parts of the circuit, and the degree of moisture in the air surrounding them. It is advisable to dry the compartment in which the electrometric tubes are placed which serves simultaneously as an electromagnetic shield and protector against the effect of external light. This should be done by placing calcium chloride, or better still, phosphorous pentoxide in the compartment. A series of observations carried out earlier in connection with the improvement of the control grid insulation of the tube can also be used in designing circuits. Quartz, and particularly amber, serve as excellent materials in the preparation of insulators for strengthening the vital parts of the circuit which require good insulation and bushings for the tube leads in the compartment.

Table 5. Comparison of Operating Stability of Various Tubes

Tube Type	Current Required by Cathode (ma)	Sensitivity (mm/v)	Max Deflection of "zero" (mm of scale in 30 min)	Nature of "Zero" Oscillations
Normal FP 54	90	110,000	65	Rapid oscillations and slow drift
FP 54 with prolongation of activation by 5 times	90	135,000	16	Rapid oscillations
FP 54 with shielded cathode ends	85	125,000	34	Slow drift

Table 5. (Continued)

Tube Type	Current Required by Cathode (ma)	Sensitivity (mm/v)	Max Deflection of "Zero" (mm of scale in 30 min)	Nature of "Zero Oscillations
FP 54 with oxide cathode	120	160,000	13	Rapid oscillations
Double tube with thoriated cathode	90	56,000	11	Oscillations and drift
Same, with oxide cathode	120	70,000	3	Small rapid oscillations

The inadequate stability of the supply source, to a significant extent, is compensated for by using storage batteries with as large as possible reserve capacity and discharge current and sufficiently long operation of the circuit in the switched-on state (up to 20 - 70 hours) before making the measurements. Beside this, the oscillation of the supply voltage source is well compensated for by use of two-tube balanced circuit. However, balancing circuits do not eliminate the influence of oscillations in the cathode emission since these oscillations are different for the two tubes operating in the circuit.

As was shown in the thorough investigations of Lafferty and Kingdon /6/ oscillations in the zero position of the galvanometer in the output circuit of electrometric layouts can be of two kinds, namely, (a) comparatively rapid oscillation of the zero point, and (b) its relatively slow deflection, frequently toward one side (drift). The basic reason for this type of operating instability of the circuit, and especially the drift, is the supplementary activation of the cold ends of the cathode continuing uninterruptedly during its time of operation. Increasing the duration of cathode activation, 5 fold, decreased the drift significantly. The rapid zero oscillation could be eliminated by shielding the ends of the filament, whereby the plate current was received only from its well-activated hot center sections. Replacing the thoriated tungsten with an oxide filament eliminates the drift almost completely, but produces considerable rapid zero-oscillation. The results of all these experiments are shown in Table 5.

All of these oscillations cannot be eliminated by operating two tubes in a balanced circuit. Therefore, for operating in such circuits, a double electrometric tube construction was proposed (Figure 6) in which the cathode and anti-space-charge cathode grid were designed along the same lines as in Tube FP 54. The two control grids and two plates which make up the halves of the grids and plates of this tube are arranged symmetrically on both sides of the cathode. Although the sensitivity of a balanced circuit operating with such a tube is decreased to one fourth of the sensitivity of a one-tube circuit with an ordinary tube Type FP 54 (half -- due to the use of a balanced circuit, and half due to the plate current and the steepness of the characteristic), nevertheless, the operating stability of the circuit with such a tube, as can be seen from Table 5 is increased considerably. This is explained by the circumstance that, due to the influence of the space charge, the oscillations of the cathode emission produce similar oscillations in the plate currents of both halves of this tube, which compensate each other during operation in a balanced circuit.

A similar tube is known as the "FP-54-split." Tubes analogous to it are GL 5674, which is like the ordinary FP 54 tube in external appearance, since only one of its control grids is well-insulated; and the tube type DBM 2. Since in the case of V-shaped filaments of the type in the FP 54 tube, it is difficult to attain complete symmetry of both halves of the twin-tube, in the DBM 2 tube type a straight filament is used [7, 8]. Still greater symmetry is obtained in the double tube of the DBM 6A type with an oxide heater cathode [8]. The basic parameters of double electrometric tubes are shown in Table 6. The operating stability obtained with these tubes in a balanced circuit can be expressed in millivolts with 1 percent change in filament current. This is graphically characterized by the following results: the ordinary type FP 54 tube gives a stability of 50 - 100 mv in a simple one-tube circuit, the double FP 54 type tube gives 10 - 20 mv, and the DBM 6A tube type--only 2 - 5 mv. In a special circuit, in which the fluctuations in the voltage source supplying the electrodes is compensated for, it was possible to reduce these values for the DBM 6A tube to 0.1 mv [8].

Table 6. Basic Parameters of Double Electrometric Tubes

Type	Cathode	U_f (v)	I_f (amps)	U_a (v)	U_{g1} (v)	U_{g2} (v)	I_{ao} (ma)	I_a (mu a)	I_{g2} (a)	S (mua/v)	C_{g2} (mmf)	Firm
FP 54-split with oxide cathode	oxide	1.5	.12	6	4	-4	--	60	$5 \cdot 10^{-15}$	25	6.5	GE
GL 5674	Thori-ated	3.8	.09	6	6	-3.5	.1	--	$5 \cdot 10^{-15}$	20	6.8	"
DBM 2	Thori-ated direct	2.	.09	8	6	-3	.3	--	$<10^{-13}$	25	7.0	Ferranti
DBM 6A	Oxide heater	4.	.24	8	6	-3	.3	--	$<10^{-13}$	40	--	"

NOTE: Parameters given separately for each system.

Insufficient mechanical durability and rigidity of the construction of many electrometric tubes leads to the appearance of so-called microphonic effect in the case of portable apparatus or with the presence of vibrations in stationary installations produced, for example, by motors. To avoid microphonic effect the tube panels may be braced on sponge rubber strips and their connections into the circuit made with flexible conductors. Due to the small dimensions of the tubes themselves, as well as their parts, subminiature and small-size type tubes possess the most durable and rigid construction and are least subject to vibration which causes microphonic effect. For this reason they are used in portable apparatus.

Application of Standard Mass Production Type Electronic Tubes in Electometric Circuits

In the case of normal operating conditions, the majority of standard receiver-amplifier tubes have grid currents of the order of 10^{-6} -- 10^{-7}, rarely

10^{-8} amps. By making them operate at lower cathode temperatures and lower potentials on all other electrodes, it is possible to lower these values to 10^{-9} -- 10^{-10} amps. Only with specially selected specimens of certain type tubes is it possible to obtain still lower values of grid current. The reason for this, in most cases, is that the control grid nearest to the cathode has the best insulation, and seldom is there found a tube type suitable for satisfactory use in the special circuits of the electrometric tetrode or inverted triode. In this respect, many types of socketless tubes are more suitable for such operation, for example, the series of miniature and subminiature tubes or "acorn" type tubes. In these types of tubes all the electrodes have about the same conditions of insulation and it is easier to use them successfully in low-voltage systems of electrometric circuits, thereby obtaining much smaller grid currents, reaching 10^{-12} -- 10^{-13}, and sometimes even 10^{-14} amps.

Thus, the 959 acorn-type tube, which is a direct filament pentode, inserted in the circuit shown in Figure 7, can produce in an electrometer system of the inverted triode type grid current of the order of 10^{-12} -- 10^{-13} amps., if, of course, the tube envelope is covered with a coating of ozocerite or with an organic silicate compound, and the filament is heated by a current of the order of 42 - 44 ma instead of the normal 50 ma. Table 7 shows some examples of the utilization of mass production types of electronic tubes in electrometric circuits. In the case of the UX 222 pentode type, the input resistance of the order of 10^{14} ohms is explained almost solely by the positive ion current from the cathode, and to a smaller extent, by leakage along the insulation. The reason for this is the utilization of the lead connection made through the envelope dome of the tube as the controlling first grid.

Table 7. Operating Conditions for Mass Production Type of Electronic Tubes in Electrometric Circuits

Tube Type	UX 222 (tetrode)			959 (pentode)	
Condition	Normal	Electrometer Circuit		Normal	Electrometer Circuit
U_f (v)	3.3	1.25	1.20	1.25	-
I_f (amps)	132	--	--	50	42 - 44
U_a (v)	135	1.5	3.0	135	6
U_{g1} (v)	1.5	Control	Amplifier with free grid	-3	Connected to the cathode
U_{g2} (v)	67.5	12	12.5	67.5	12
U_{g3} (v)	--	--		Connected with cathode	Control (Fig 7)
I_a	3.7 ma	0.07 mu a	2.6 mu a	1.7 ma	--
I_g control (amps)	$< 10^{-6}$	$\sim 10^{-13}$	$\sim 10^{-10}$	$< 10^{-6}$	10^{-12} - 10^{-13}
R_g (ohms)	--	10^{14}	10^{11}	-	10^{13} - 10^{14}
Sensitivity of apparatus in the plate circuit (amps/mm)	--	$3 \cdot 10^{-10}$	10^{-10}	--	10^{-9} - 10^{-10}

/Appended figures follow./

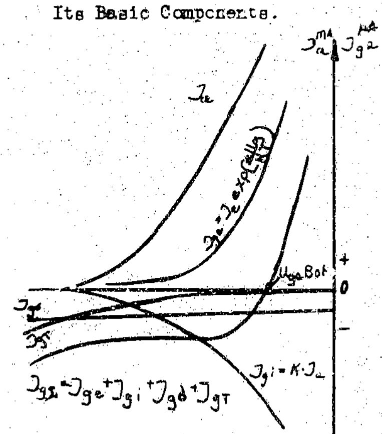

Figure 1. Grid Current Characteristic and Its Basic Components.

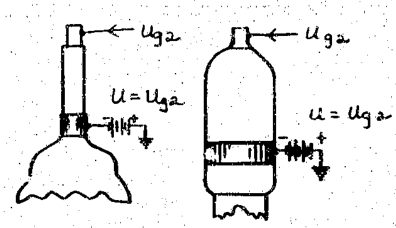

Figure 2. Protective Ring Decreasing the Leakage Along the Bulb.

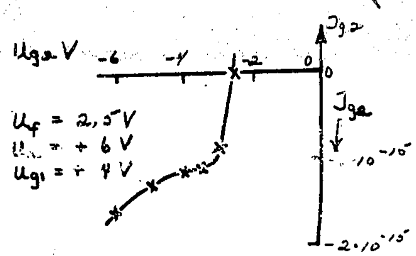

Figure 3. Grid Current of the Type FP-54 Tube.

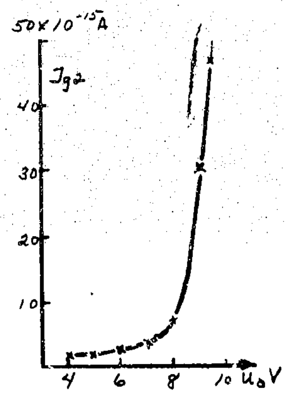

Figure 4. Dependence of Grid Current on Plate Voltage.

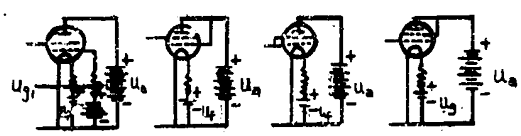

Figure 5. Wiring Diagram for an Electrometric Tetrode.

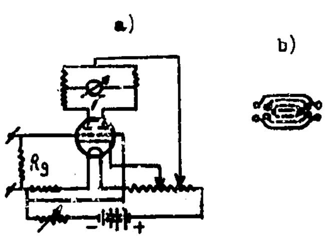

Figure 6. Principal Wiring Diagram and Construction of Electrodes of Double Electrometric Tetrode.

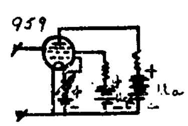

Figure 7. Circuit for Using Acorn Type 959 Pentode as an Electrometric Tube.

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